



北京大学

PEKING UNIVERSITY

# Test beam performance of sensor modules for the CMS Barrel Timing Layer

14<sup>th</sup> Beam Telescopes and Test Beams Workshop  
Mainz – 14 April 2026

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# The High-Luminosity LHC



## Scenario:

- 3-4 times higher instantaneous luminosity
- higher Pile-Up (40-60  $\rightarrow$   $\sim$  200 events)
- Unprecedented amount of collisions data!

## Challenge:

- Increased spatial overlap of vertexes  $\rightarrow$  up to 5x higher vertex density
- Degradation in track-vertex association and event reconstruction
- Timing information useful to recover  $\sim$  Run 2 performances



CMS Experiment at the LHC, CERN  
Data recorded: 2025-Oct-08 20:55:40.834048 GMT  
Run / Event / LS: 397962 / 179871689 / 556

PU  $\sim$  200  
 $\Delta t \sim$  180 ps

$\sim$  10 cm

Exceptionally High PU event  
(CMS - 2025) @ LHC

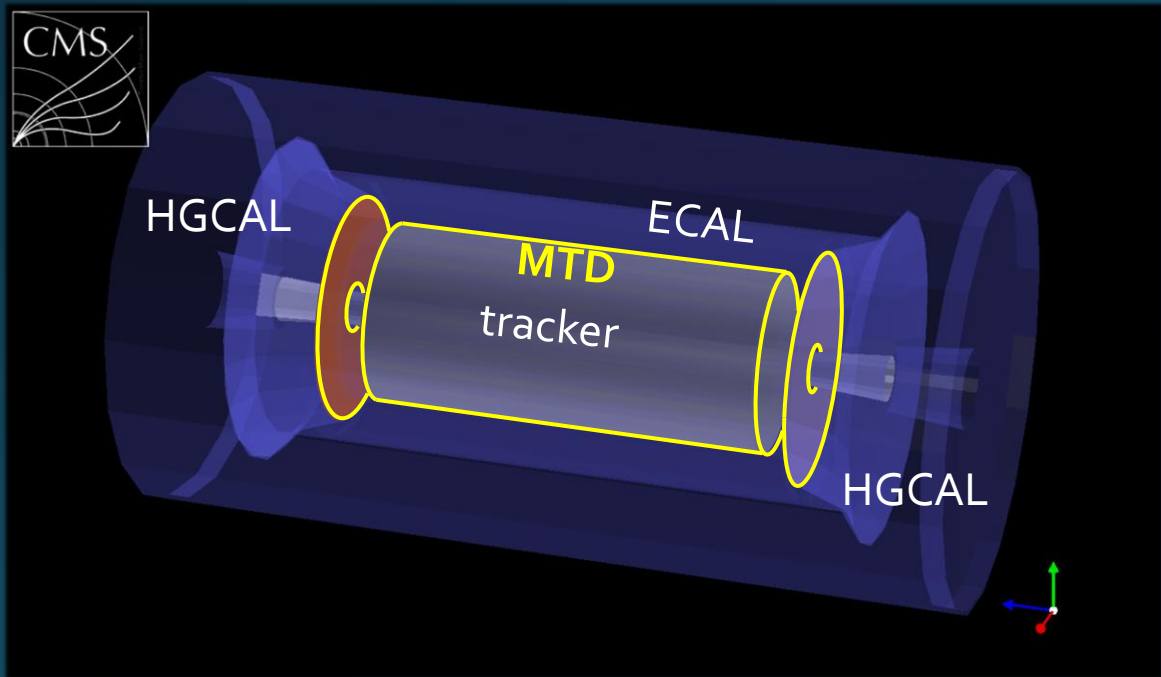


The norm @ HL-LHC

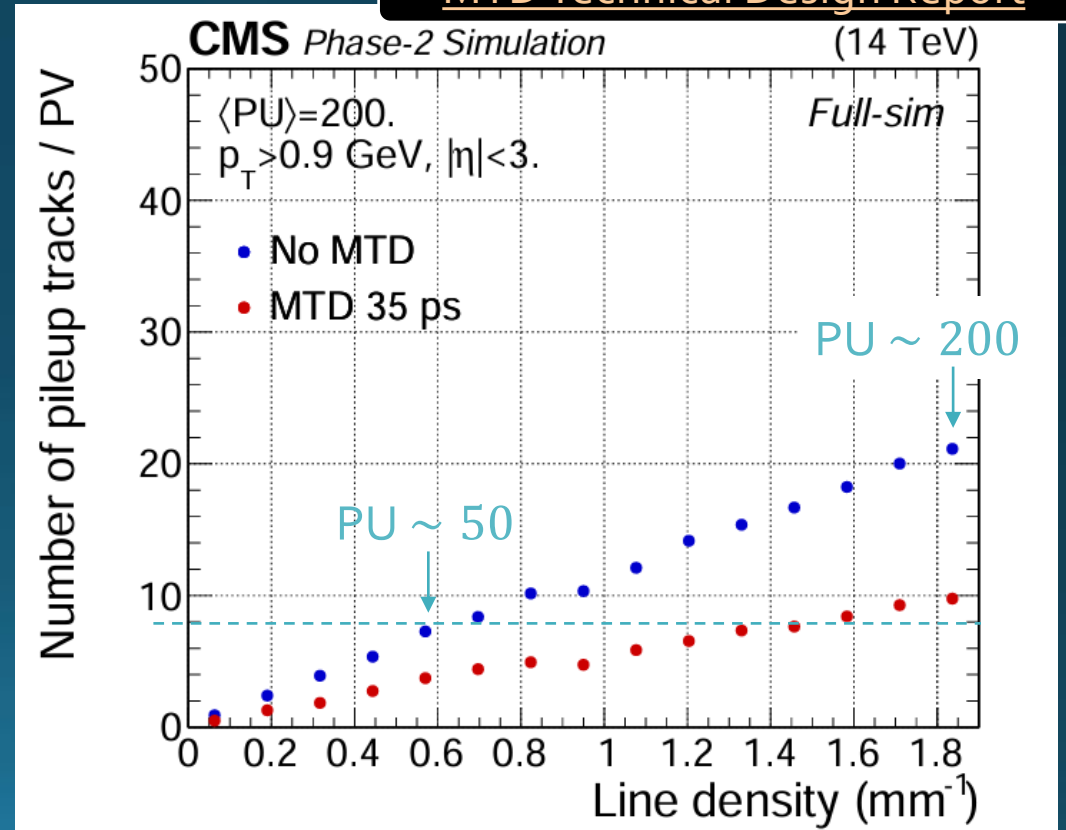
# The MIP Timing Detector

New CMS layer for High-Luminosity LHC (HL-LHC):

- Time measurement of **min.-ionizing (charged) particles (MIP)** with resolution of **30-60 ps**
- Reduce effective PU at HL-LHC using timing information
  - Time tagging MIPs: 3D  $\rightarrow$  **4D vertex reconstruction**



**MTD Technical Design Report**



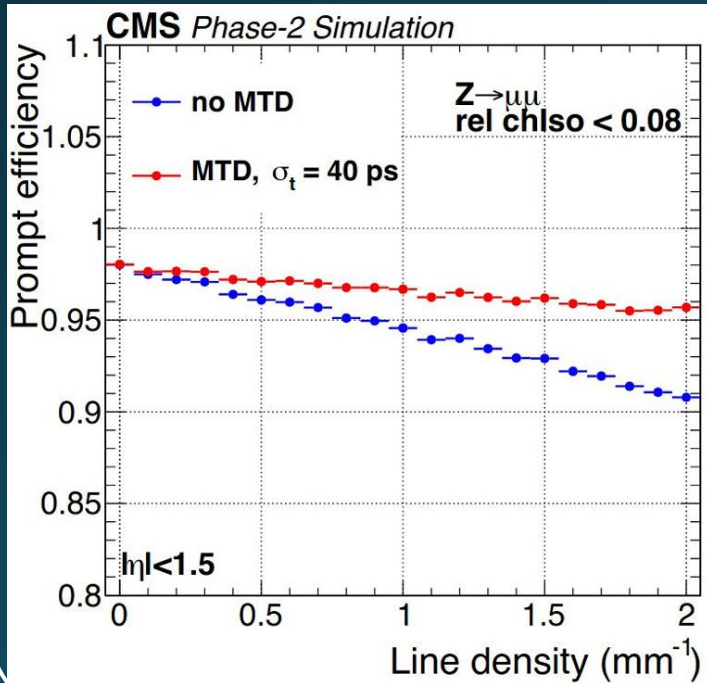
# MTD impact on physics

- Improvement in identification, reconstruction and resolution of physics objects

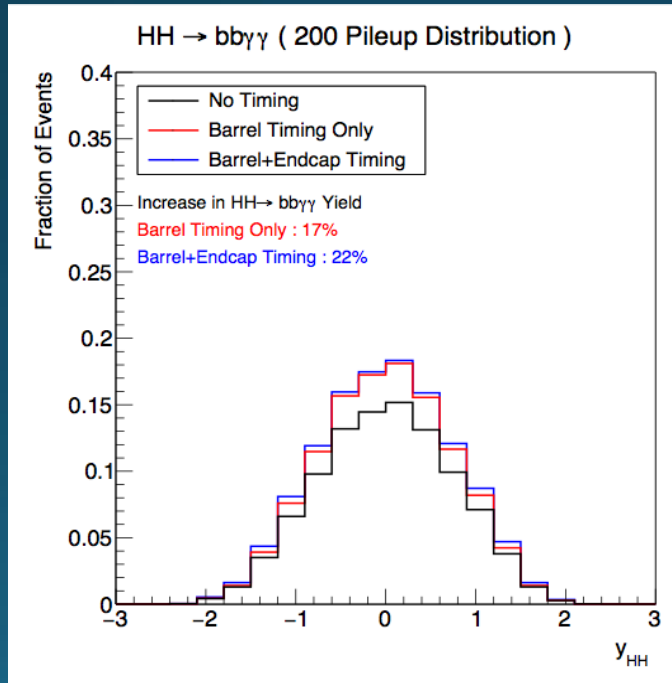
- Higher sensitivity for rare processes

- Timing information to increase sensitivity to exotic time signatures or particle identification

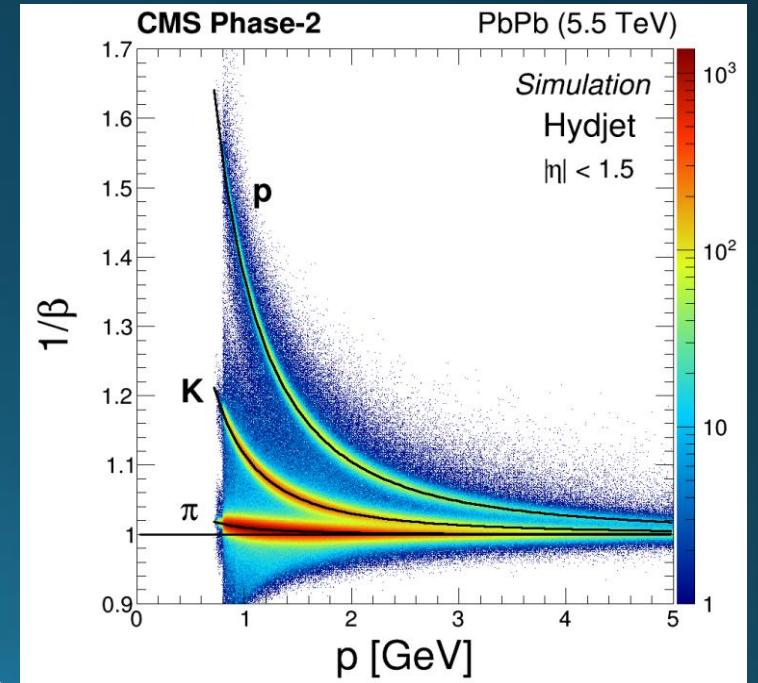
## Z → μμ efficiency increase



## HH → bbγγ yield increase



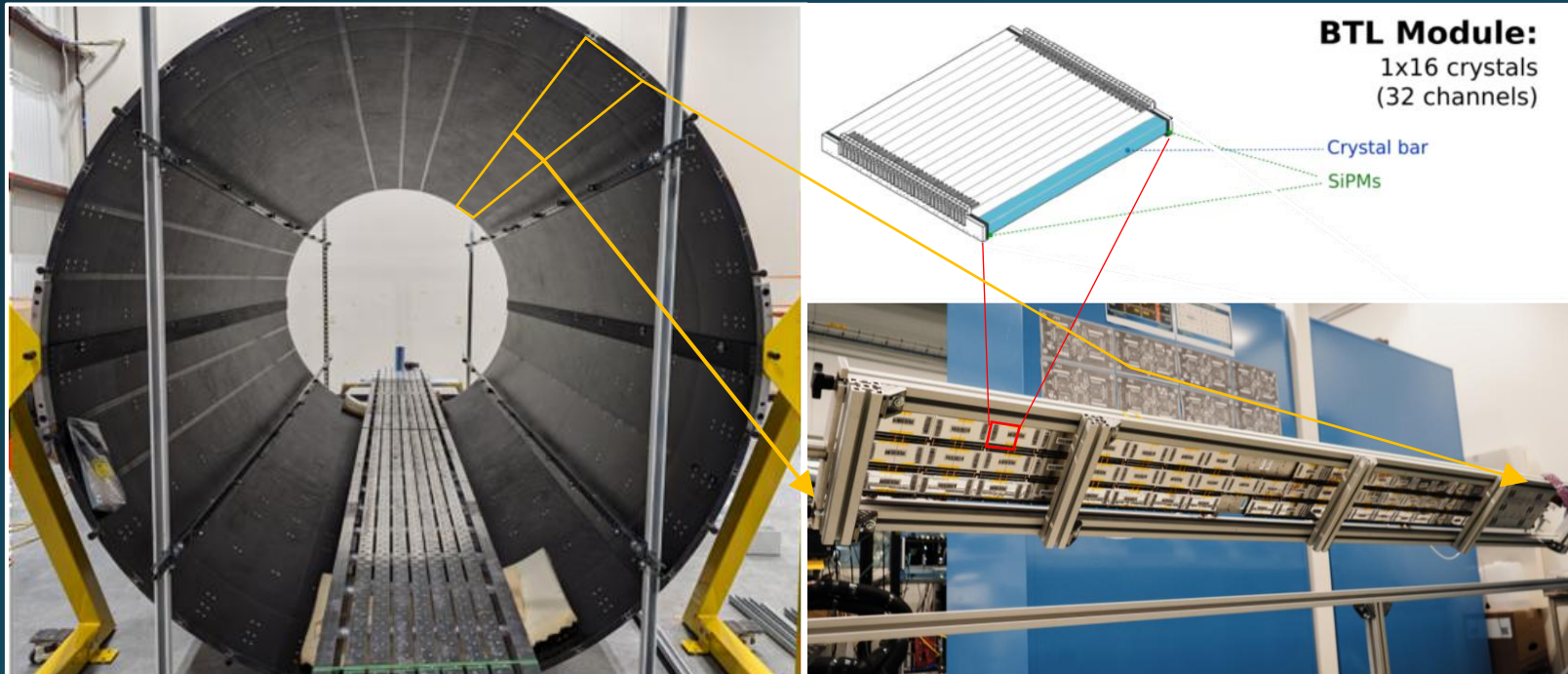
## Particle ID via time-of-flight



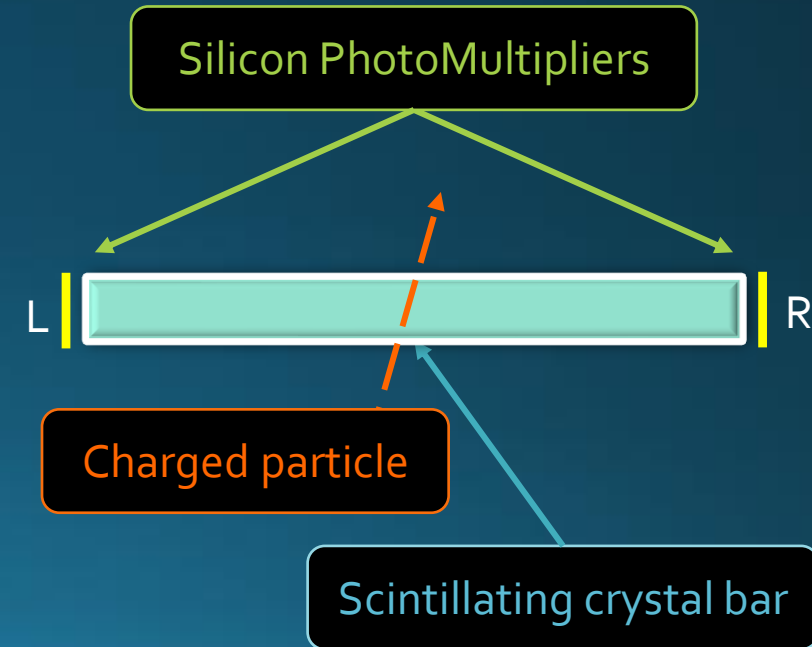
# The MTD Barrel Timing Layer

- **BTL requirements**

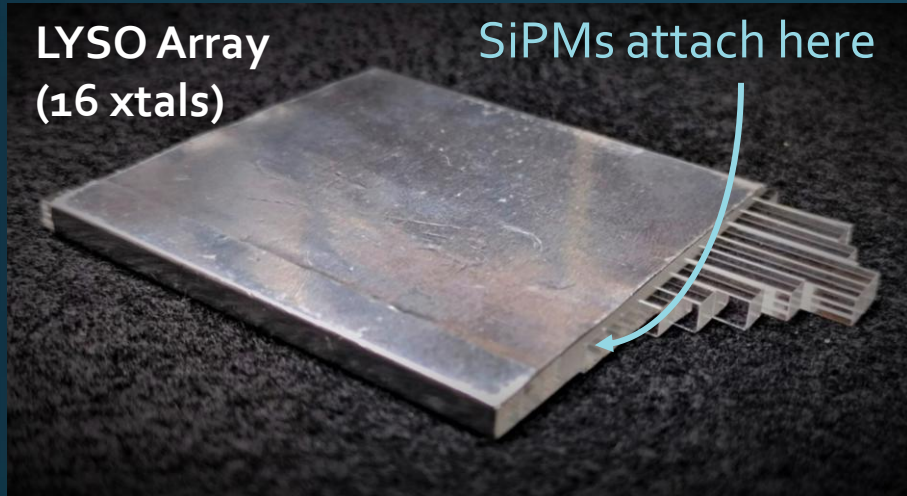
- Radiation hardness ( $1.9 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$  end of HL-LHC)
- Negligible impact on calorimeter performance (small energy absorption)
- Mechanics, service, cost and schedule compatible with existing upgrades



[BTL-Tracker Support Tube \(BTST\) - CERN Document Server](#)



# BTL Sensors

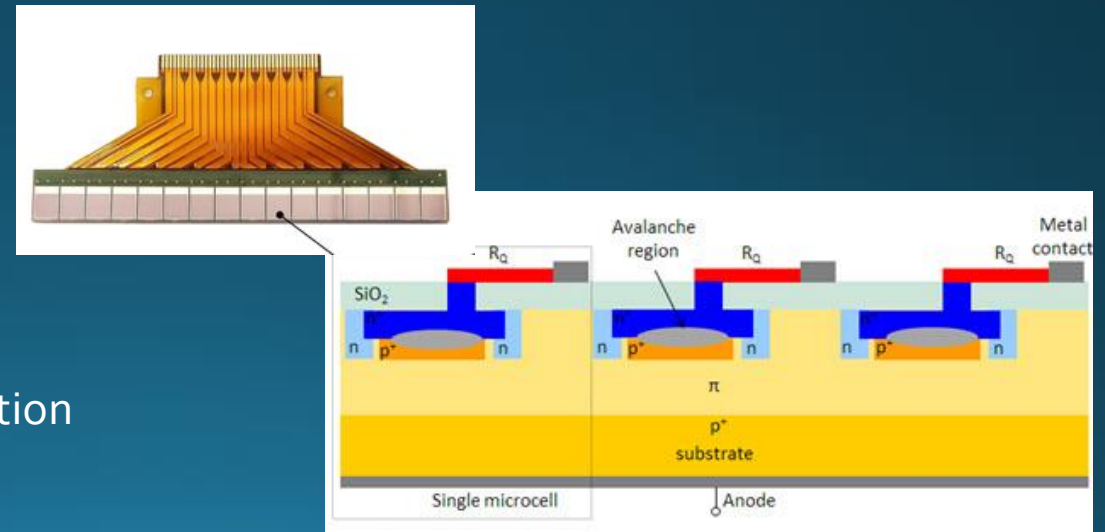


## Cerium-doped Lutetium-Yttrium Oxyorthosilicate (LYSO:Ce)

- Rise time:  $\tau_r \simeq 100$  ps
- Decay time:  $\tau_d \simeq 40$  ns
- High Light Yield:  $LY \simeq 40\,000$  ph/MeV
- High mass density ( 7 - 7.3 g/cm<sup>3</sup> )
- Radiation hardness
- Easy availability (used in medical applications such as PET)

## Silicon PhotoMultiplier (SiPM)

- Matrix of Avalanche PhotoDiodes (APD) in reverse bias
- Avalanche mechanism  $\rightarrow$  Internal gain
- Compact and robust
- Insensitive to magnetic fields
- Operate at relatively low voltages with low power consumption
- Photo-Detection Efficiency, **PDE** up to 50%



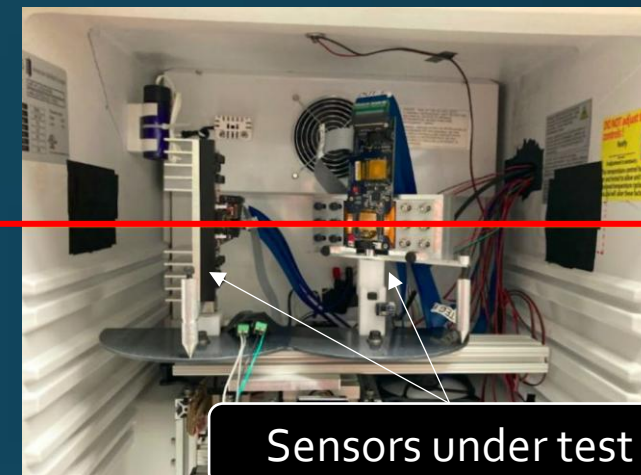
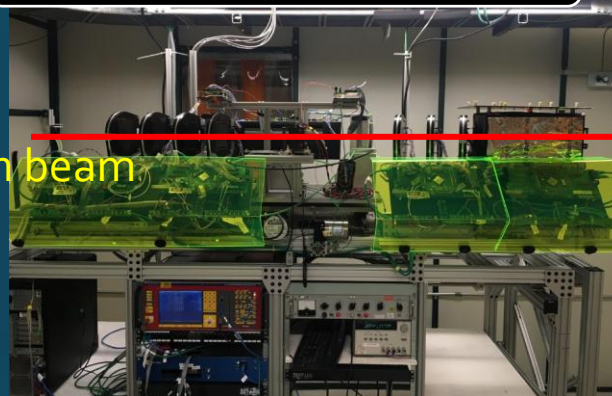
# Latest testbeam campainings

## March 2023 @FNAL

- sensor modules with 10-15-25  $\mu\text{m}$  cell-size SiPM and different LYSO thickness
- Only non-irradiated sensors

FNAL testbeam Telescope

proton beam

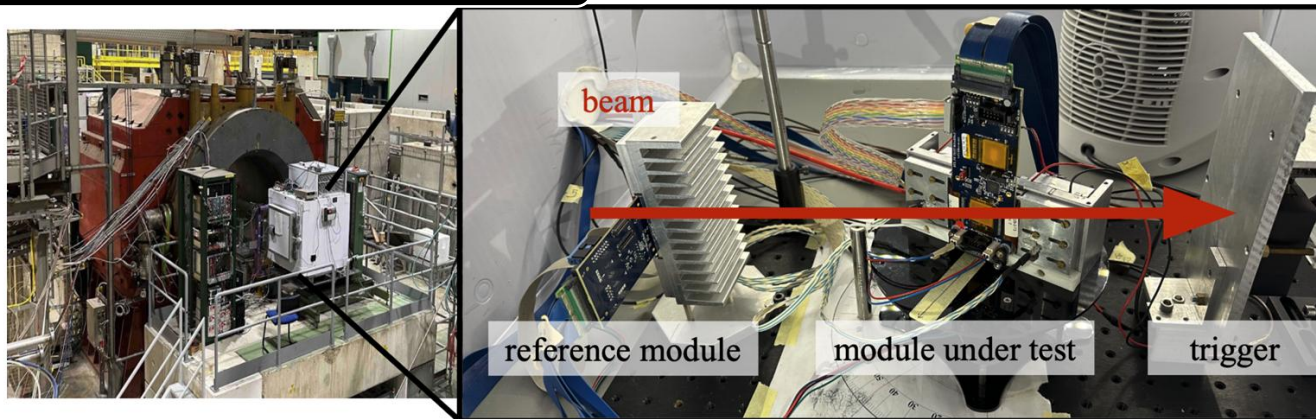


Sensors under test

## June and Sep. 2023 @CERN North Area (H8)

- sensor modules with various SiPM cell size and different LYSO thickness
- both non-irradiated and irradiated sensors
- Temperature range from  $-45^{\circ}\text{C}$  to  $5^{\circ}\text{C}$  emulating different ageing conditions

CERN North Area(pion beam)



tracking system  
(wire chambers)

reference  
module

module  
under test

trigger  
(plastic scintillator)

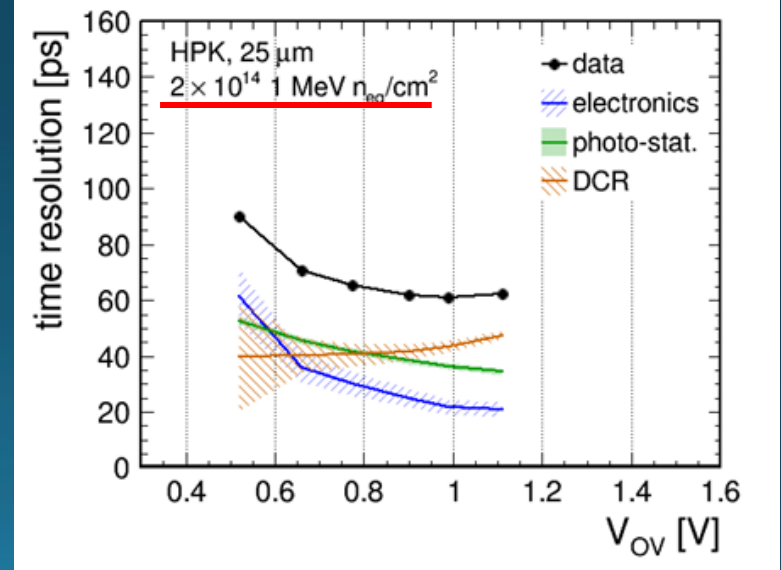
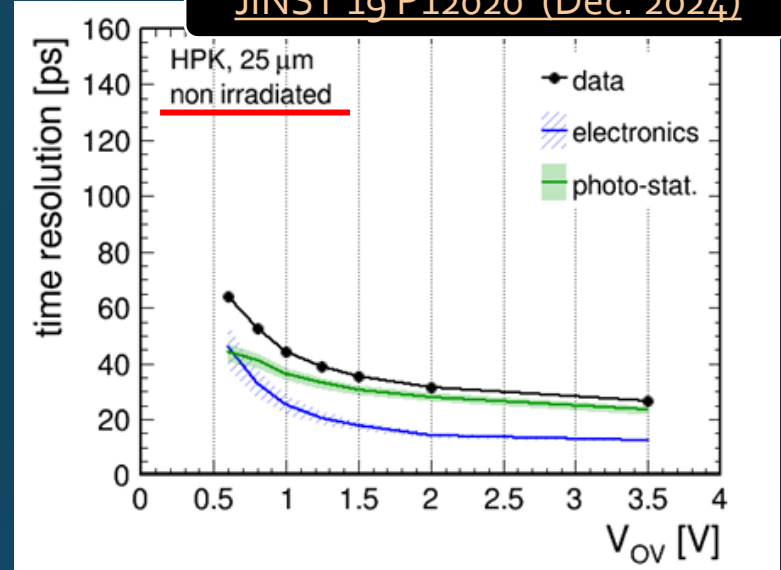
# BTL Time Resolution

JINST 19 P12020 (Dec. 2024)

$$\sigma_t^{\text{BTL}} = \sigma_t^{\text{clock}} \oplus \sigma_t^{\text{digi}} \oplus \sigma_t^{\text{ele}} \oplus \sigma_t^{\text{phot}} \oplus \sigma_t^{\text{DCR}}$$

$$\sigma_t^{\text{ele}} \propto \frac{1}{\text{Gain} \cdot N_{\text{phe}}} \quad \sigma_t^{\text{phot}} \propto \sqrt{\frac{1}{N_{\text{phe}}}} \quad \sigma_t^{\text{DCR}} \propto \frac{\sqrt{\text{DCR}}}{N_{\text{phe}}}$$

- **Electronic noise  $\sigma_t^{\text{ele}}$** 
  - Scales with the steepness of the electronic signal
  - Highly dependent on SiPM bias voltage and cell size
- **Photo-statistics term  $\sigma_t^{\text{phot}}$** 
  - Stochastic fluctuations in the time-of-arrival of photons at SiPM
- **Dark Count Rate  $\sigma_t^{\text{DCR}}$** 
  - Induced by radiation damage
  - Tested after SiPM irradiation with  $2 \times 10^{14} \text{ MeV } n_{\text{eq}}/\text{cm}^2$  (expected HL-LHC fluence)
  - **Dominant term for irradiated SiPMs**

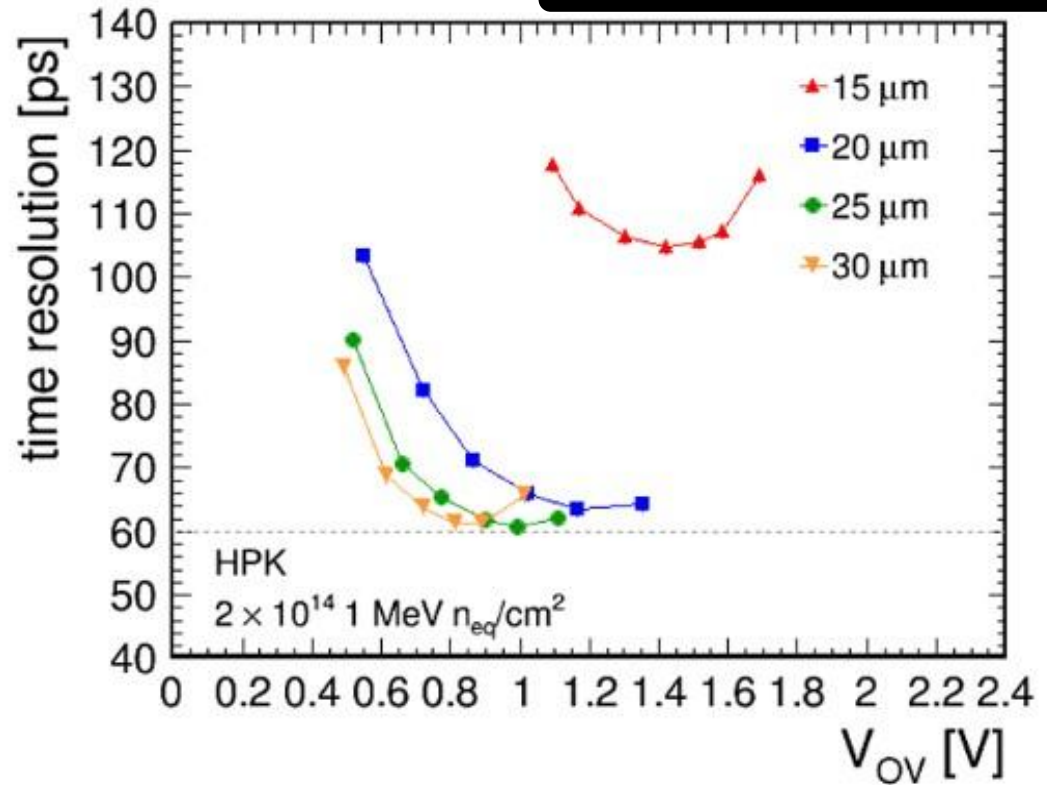
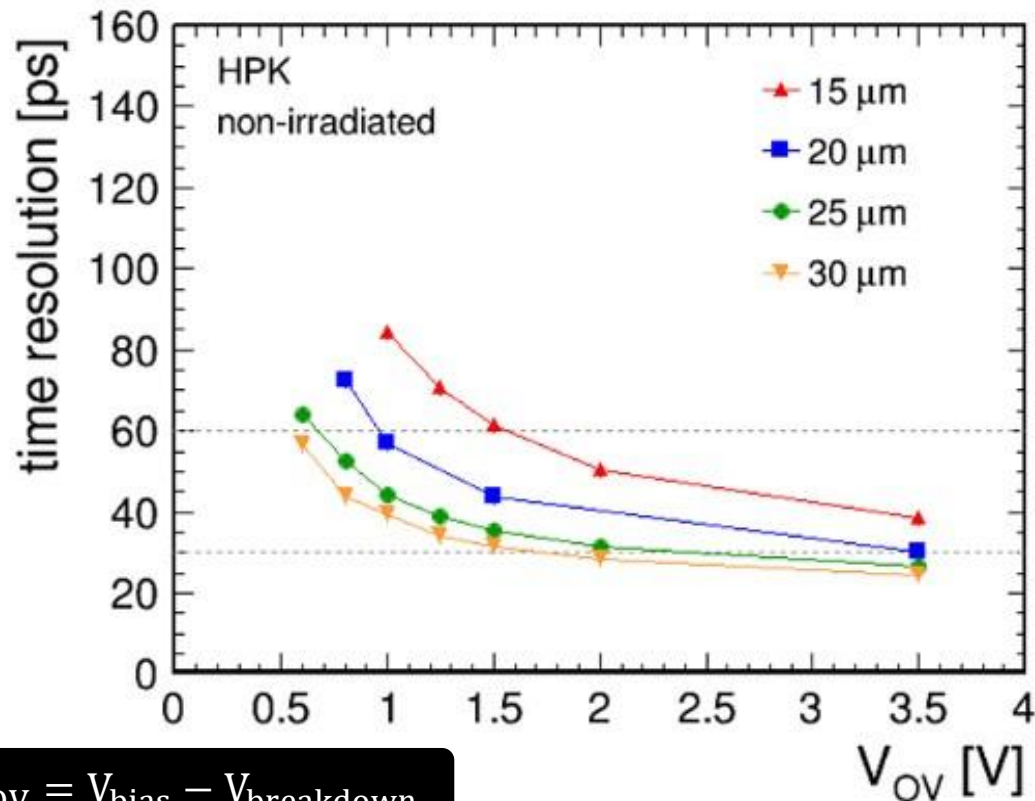


# BTL Sensors Optimization: SiPM

**SiPMs with different cell size:** 15 $\mu\text{m}$ , 20 $\mu\text{m}$ , 25 $\mu\text{m}$ , 30 $\mu\text{m}$

- larger cells  $\rightarrow$  higher Gain and PDE, but larger DCR for irradiated modules
  - 25 $\mu\text{m}$ : best overall performances before/after irradiation

JINST 19 P12020 (Dec. 2024)



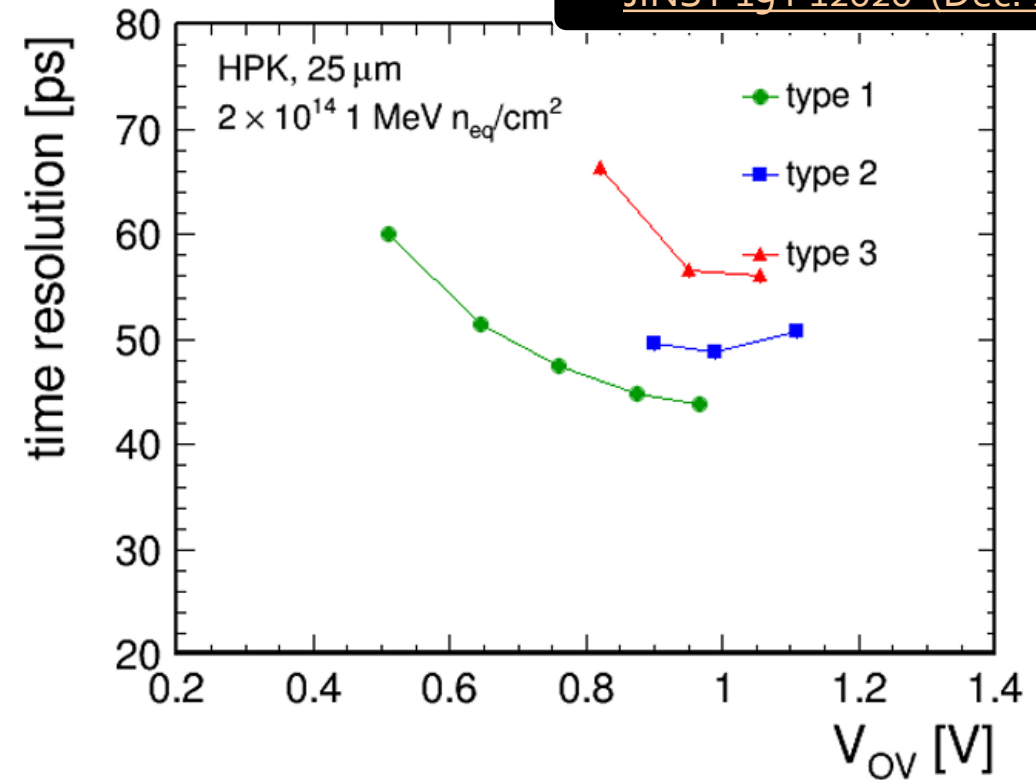
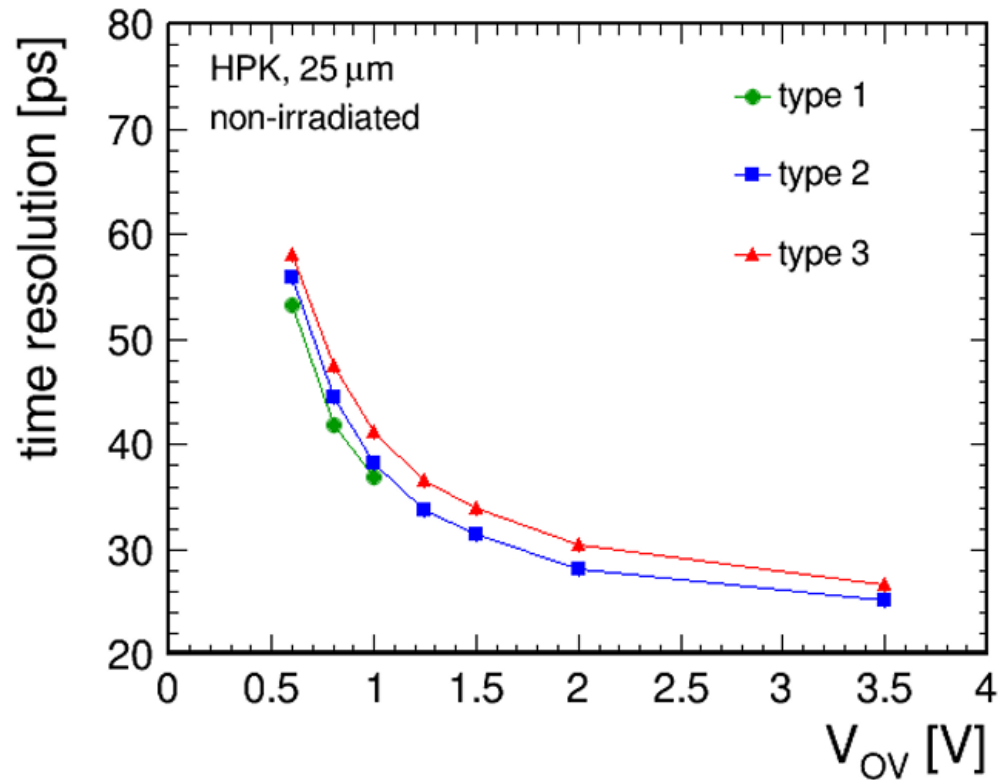
$$V_{OV} = V_{bias} - V_{breakdown}$$

# BTL Sensors Optimization: LYSO

**LYSO crystals of thickness:** 3.75mm (type 1), 3.00mm (type 2), 2.75mm (type 3)

- Thicker crystals  $\rightarrow$  larger energy deposit in LYSO
  - Limited by available space, material budget before calorimeters, and material cost

JINST 19 P12020 (Dec. 2024)

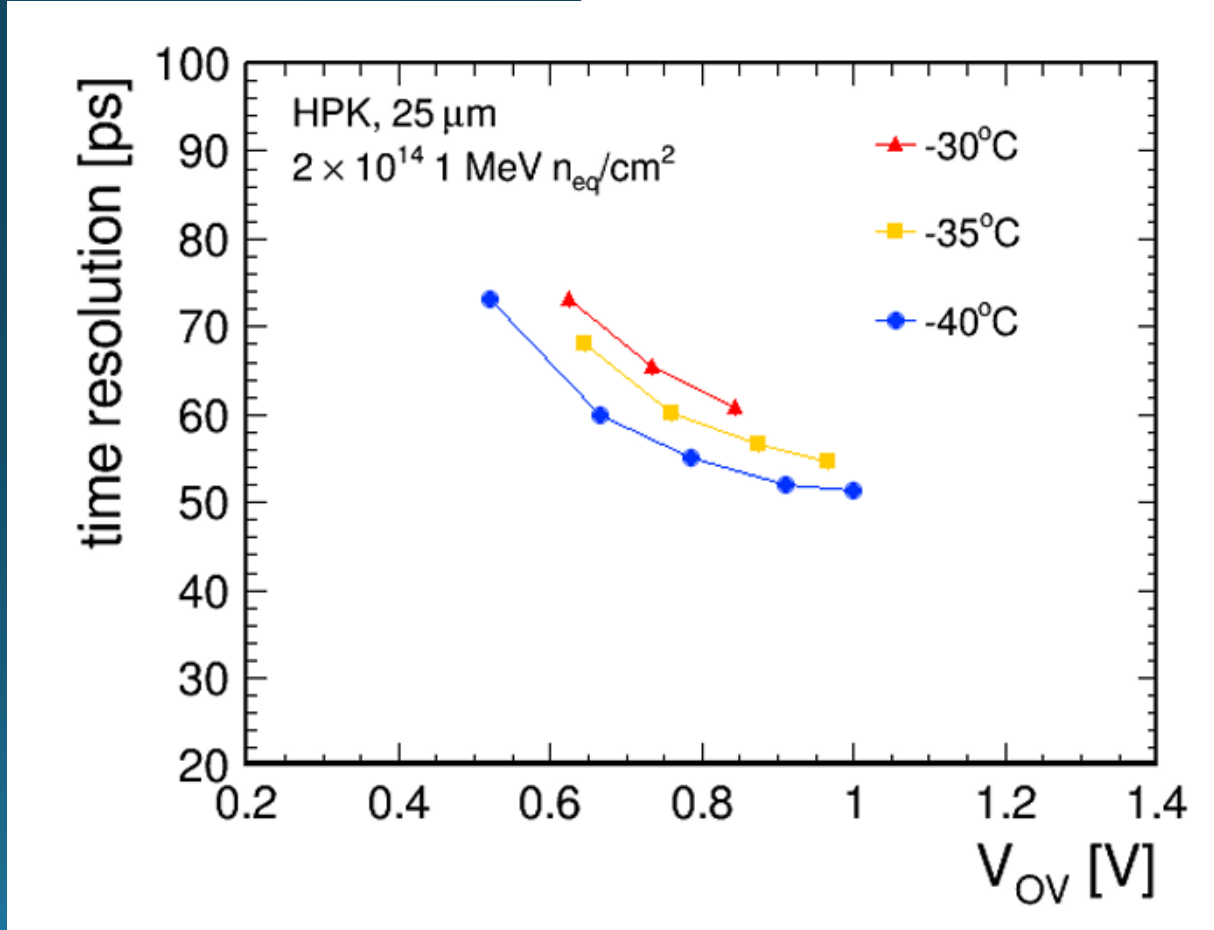
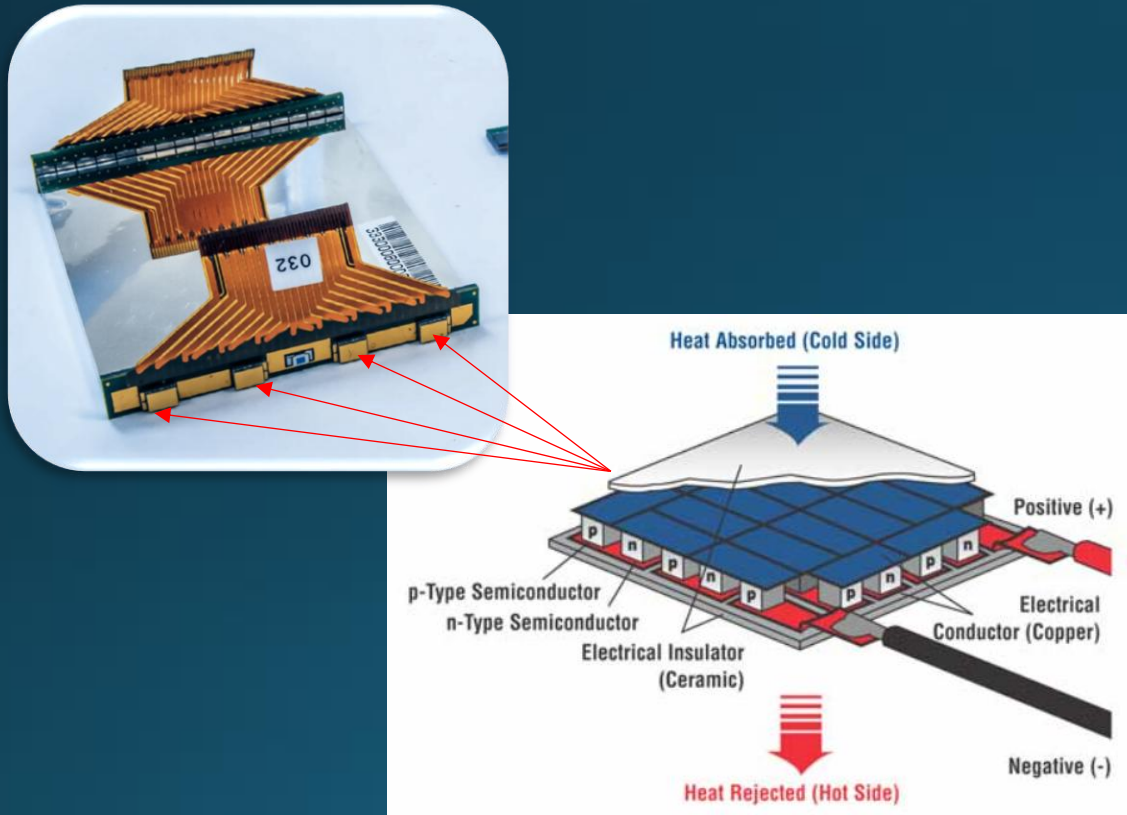


# BTL Sensors Optimization: TECs

The DCR term is reduced at cold temperatures:

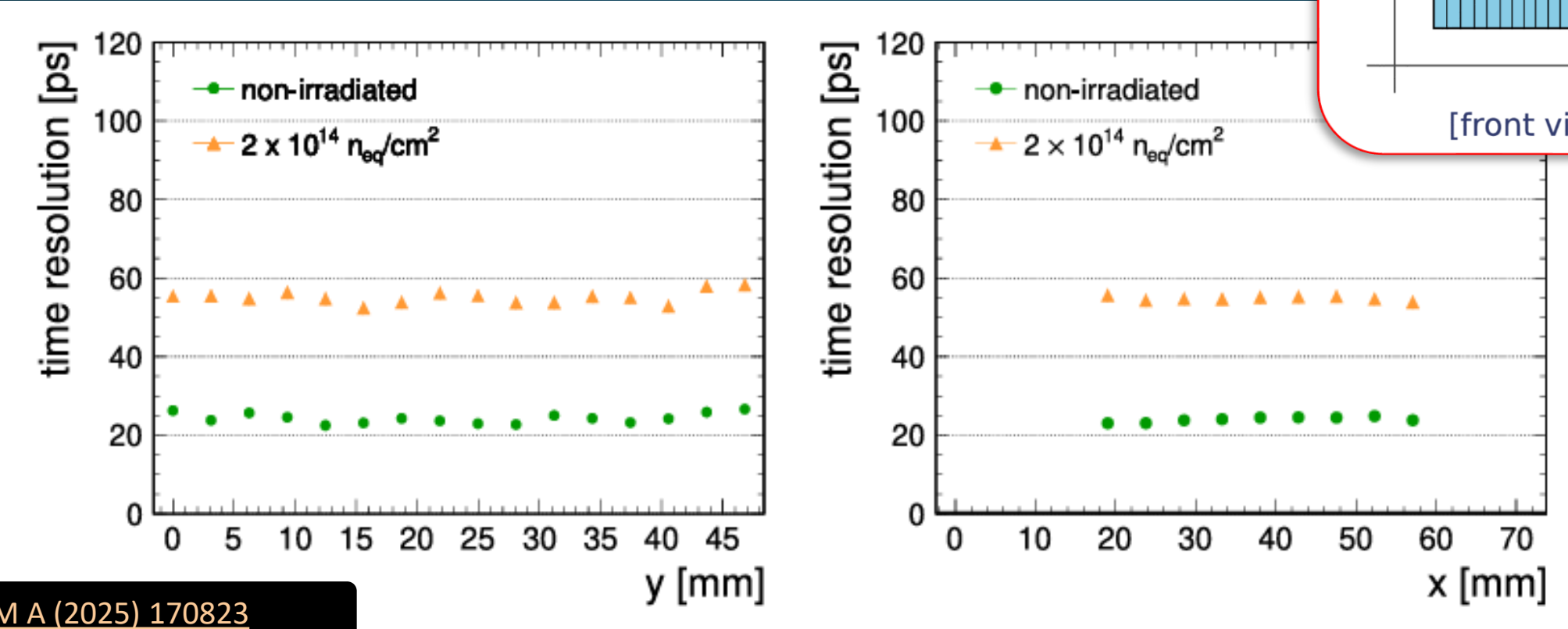
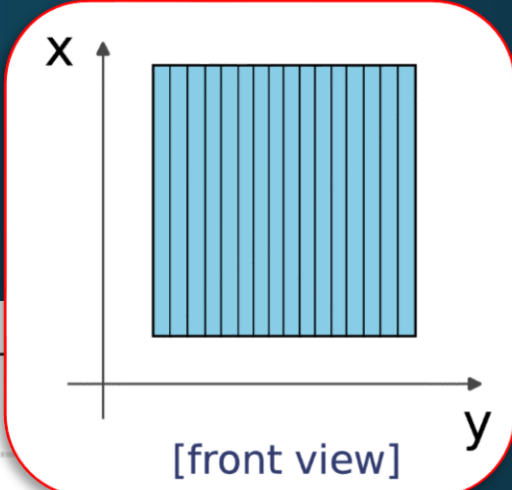
- Inserted Thermo-Electric coolers (TECs) on SiPMs to lower the operating temperature below  $-35^{\circ}\text{C}$
- Could also be used in HL-LHC stops for **annealing at  $+60^{\circ}\text{C}$**

JINST 19 P12020 (Dec. 2024)



# Time resolution uniformity

- The time resolution among crystals in a module is **uniform within 2ps RMS**, both along one bar (x) and across different bars (y)

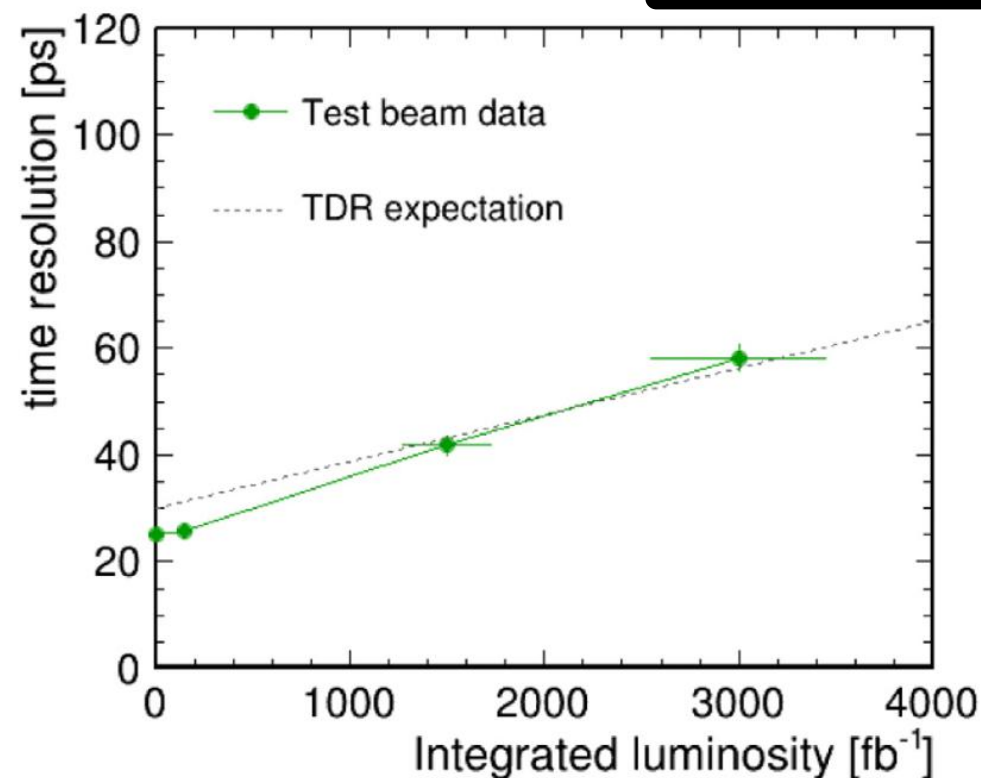
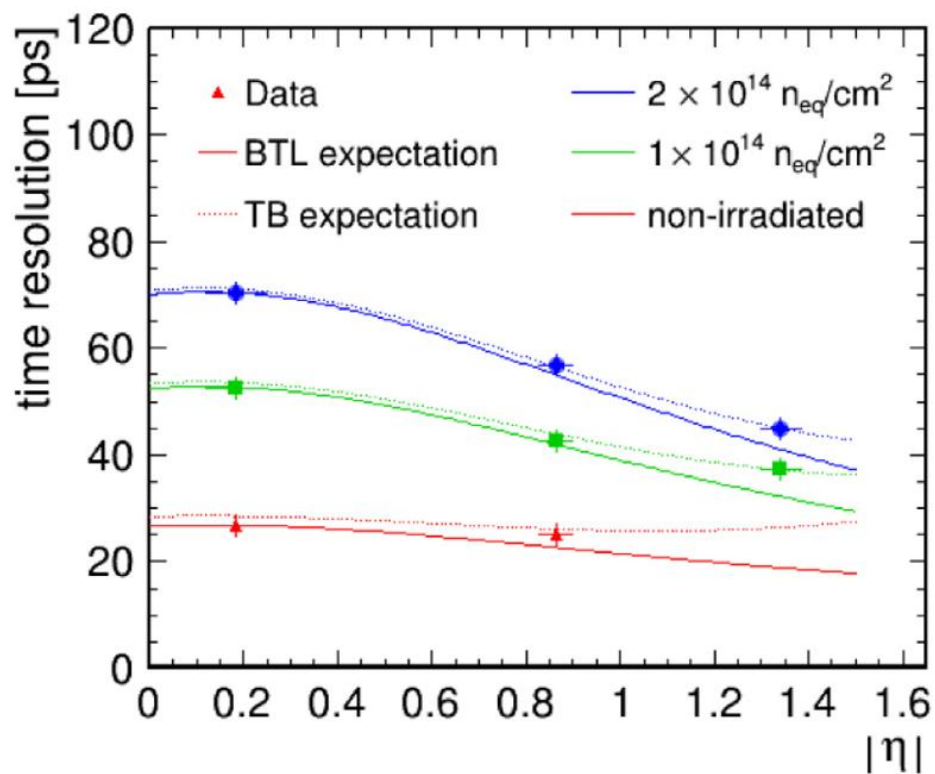


[NIM A \(2025\) 170823](#)

# The full picture

- Testing BTL modules over a **range of incident angles and irradiation conditions** confirms the expected timing performance across all detector regions and for different ageing scenarios.

NIM A (2025) 170823



# Summary

- **Optimized BTL design finalized following in 2023 test-beam campaigns**
  - Performance was validated under CMS-like operating conditions
- **BTL assembly now in full swing**
  - A **substantial fraction** of the detector already assembled at Peking University, Milano-Bicocca, CalTech, and Virginia University
  - A significant share of trays **delivered to CERN**
  - Detector insertion planned for the coming months
- **Additional round of test-beam campaigns at CERN (Sep. 2025, Apr. 2026)**
  - Providing deeper insight into the correlation between module quality and timing performance
  - Enabling **further optimization of the calibration strategy**
  - Validating the **full readout chain**
  - Data taking and analysis are ongoing → more results to come

Tray arrival at CERN Sep 25

